IOP Conf. Series: Materials Science and Engineering **966** (2020) 012107 doi:10.1088/1757-899X/966/1/012107

Synchronous reluctance machines: performance evaluation with and without ferrite magnets

Mohamed N Ibrahim[1,2,3,6], Kotb B Tawfiq[1,2,4], E M Rashad[5] and Peter Sergeant[1,2]

[1]Department of Electromechanical, Systems and Metal Engineering, Ghent University, Ghent, Belgium

[2]FlandersMake@UGent – corelab EEDT-MP, Leuven, Belgium

[3]Electrical Engineering Department, Kafrelshiekh University, Kafrelshiekh, Egypt

[4]Department of Electrical Engineering, Faculty of Engineering, Menoufia University, Menoufia, Egypt

[5]Electrical Power and Machines Department, Tanta University, Tanta, Egypt

E-mail: [6]m.nabil@ugent.be

Abstract. Nowadays, a great interest in the efficiency and the cost of electrical machines has been noticed. Therefore, Synchronous Reluctance Motors (SynRMs) have become more attractive alternative for induction and permanent magnet (PM) synchronous machines in several industrial applications. This is because they do not use rare-earth magnets, windings and cages in their rotor. Consequently, the cost and efficiency are improved. Nevertheless, a major problem of the SynRMs is the low power factor. To improve the power factor as well as the torque density and efficiency, the cheap ferrite PM can be inserted in the rotor, resulting in the so called 'PM assisted SynRM'. The rotor design of SynRMs with and without permanent magnets (PMs) has a huge effect on the motor efficiency, torque density and power factor. This paper introduces an evaluation for the performance of SynRMs with and without PMs in terms of efficiency, torque and power factor maps as a consequence of different rotor designs. Three different rotor designs for the same machine stator have been compared. For one machine, the experimental measurements are obtained and the validation of the simulation results are confirmed. A preprint of this work is available under: https://biblio.ugent.be/publication/8515429.

1. Nomenclature

i_d, i_q	Direct and quadrature axis stator current respectively, A
λ_d, λ_q	Direct and quadrature axis flux linkage of SynRM respectively, V.s
P	Number of pole pairs
R_s	Stator resistance of the motor, Ω
V_d, V_q	Direct and quadrature component of stator voltage respectively, V
$V_{m,}$ I_m	Maximum input voltage and current of the motor, V, A respectively
δ, α	Load angle and current angle, rad
ω_r	Mechanical speed of the rotor, rad/s

IOP Conf. Series: Materials Science and Engineering **966** (2020) 012107 doi:10.1088/1757-899X/966/1/012107

2. Introduction
Recently, Synchronous Reluctance Motors (SynRMs) with or without permanent-Magnets (PMs) are becoming attractive machines for variable speed industrial applications [1]–[5]. This is because of their merits of wide constant power speed range and high torque density. The power density and efficiency are better than that of induction machines and comparable to that of permanent magnet machines [2], [3]. In literature, there are a lot of papers which study SynRMs when their rotor includes and does not include magnets [1–16]. For example, in [1], suitable design of the three phase SynRM for electric vehicles was presented. In addition, a comparison between different flux-barrier designs for the same stator was investigated. The effect of four different steel grade on the performance of SynRMs was studied in [2]. It is noticed that the lower thickness steel grade has the higher efficiency, however it does not produce the higher output torque. In [3], the design of PMaSynRMs with an induction motor with identical NEMA frame stators was studied and compared. In [4], the design characteristics of SynRM with ferrite magnets and stator skewing was investigated. In addition, mechanical stress and demagnetization of ferrite was studied as well. In [5], the performance of PMaSynRMs for high-efficiency and wide constant power operation was studied. An investigation of the effect of the parameters and anti-demagnetization of rare-earth-less PMaSynRMs was done in [6]. In [7], a study of general properties of power losses in soft ferromagnetic materials was carried out. Different applications including pumping systems of the PMaSynRMs were introduced in [8–10] with high energy efficient. In [11] and [16], the modelling, simulation and design of the PMaSynRMs were introduced. This paper presents an evaluation for the performance of SynRMs with and without permanent magnets.

3. Performance Evaluation of SynRMs and PMaSynRMs
The vector diagram of PMaSynRM is sketched in Figure 1. Inserting $\lambda_{pm} = 0$ in Figure 1 results in the vector diagram of SynRM. The complete model of SynRM and PMaSynRM is reported in [16]. In the following section, three different rotors having identical stator and other parameters as listed in table 1 have been considered. The stator has 36 slots and 15 turns/slot with conventional star-connected windings. The stator design is similar to that of induction machines. Moreover, all the rotors have three flux-barriers per pole as shown in Figures 2 and 3. The first rotor has been designed by a manufacturing company. This motor is called a reference SynRM and it is the motor for which the experimental validation has been done. The second rotor has been optimized by a conventional optimization technique with 2D FEM for the twelve rotor parameters, described in Figure 2. This motor is called an optimal SynRM and its rotor parameters are given in table 2. The third rotor has been obtained by filling all the three flux-barriers of the optimized rotor (second one) with ferrite PMs. The ferrite PM is selected due to the lower cost and the availability in the market. In addition, it can withstand higher temperature [8]. The adopted ferrite PM properties are shown in [8]. This motor is called a PMaSynRM. The performance of the three machines is obtained by 2D-FEM at the same conditions. Sinusoidal currents are injected in the machine windings at different speeds up to the rated speed value (6000 r/min). The currents have been varied from low values up to the rated value ($I_m = 30$ A) at fixed current angle $\alpha = 56.5°$. The selected value of the current angle (56.5°) is the angle at which the machine can give approximately the maximum output power for the different currents and speeds. The FEM field pattern of the reference motor for quarter geometry at rated conditions is described in Figure 3. It can be noticed from Figure 3 that there are some iron regions having higher flux level (red color). These regions are called flux-barrier tangential ribs. The thickness of the ribs has a great influence on the performance of SynRM.

Figure 4 shows the output torque of the three machines at different operating speeds and stator currents up to the rated values. First, at the same current and speed, the output torque of the machine depends on the rotor design which is greatly affected by the design of the twelve parameters of the rotor, given in Figure 2. Therefore, an optimized rotor geometry for the SynRMs is necessary and unavoidable to maximize the machine performance. The performance of SynRM mainly depends on the quadrature (q) and the direct (d) inductances and these inductances depend on the geometrical design of the flux barriers of the rotor. Second, when comparing the subfigs of Figure 4 of optimal SynRM and PMaSynRM, it can be observed that the average torque of the machines is increased by 25 % when adding ferrite PM in the optimized rotor This is because of the effect of PMs on the q-axis inductance of the SynRM. The PMs saturate the tangential ribs (Figure 2) of the motor. By consequence, the q-axis inductance is reduced resulting in a higher output torque.

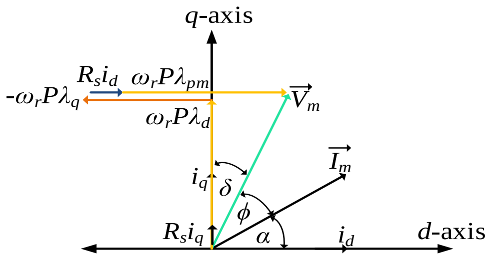

Figure 1. Vector diagram of PMaSynRM.

Table 1. Prototype SynRM parameters.

Parameter	Value	Parameter	Value
Number of poles/stator slots	4/36	Rated current/speed	22 A/6000 RPM
Number of phases	3	Material grade	M400-50A
Stator outer/	180 mm/	Axial length/	140 mm/
inner diameters	110 mm	rotor outer diameter	109.4 mm
θ_1,θ_2,θ_3	7.5°, 20.5°, 33.5°	W_1, W_2, W_3	6 mm, 4 mm, 3 mm
L_1, L_2, L_3	25 mm, 19 mm, 12 mm	p_1, p_2, p_3	23.5 mm, 36 mm, 46 mm

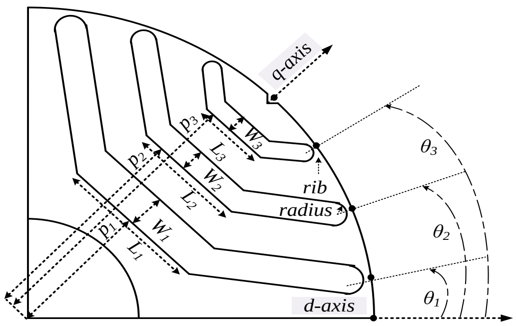

Figure 2. Quarter rotor geometry of SynRM.

Table 2. Optimal SynRM rotor geometrical parameters.

Parameter	Value	Parameter	Value
θ_1, θ_2, θ_3	8.08°,16.43°, 28.4°	L_1, L_2, L_3	28.85 mm,28 mm,13.5 mm
W_1, W_2, W_3	5.5 mm, 3.5 mm, 3.5 mm	p_2, p_1, p_3	35.5 mm, 22.75 mm, 44.2 mm

θ_r=0° θ_r=45°

Figure 3. Flux paths of the reference SynRM using FEM for a quarter geometry at two rotor positions (0 and 45°)

IOP Conf. Series: Materials Science and Engineering **966** (2020) 012107 doi:10.1088/1757-899X/966/1/012107

Figure 5 shows the computed losses (iron and copper) of the machines for different currents and speeds up to the rated values. The copper losses are constant for all the machines due to the same stator windings and currents. The iron losses depend on the material properties, the currents and the geometry design of the machine. The variation of the parameters of rotor flux-barrier, shown in Figure 2, has a great effect on the iron losses of SynRM. This is due to the variation of the saturation regions of the iron especially, the rotor tangential ribs and the teeth of the stator. This can be noticed in Figure 5, by comparing the subfigs (reference, optimal and PMaSynRM). For the same current and operating speed, the iron losses increases for the PMaSynRM that has the higher output torque (Figure 4) compared to the other machines. In addition, for one machine as expected, the iron losses increase with the increase in speed and current, approximately in proportional way.

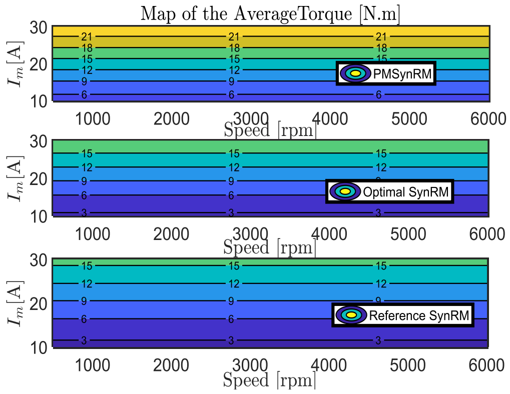

Figure 4. SynRM average torque maps for different rotor designs.

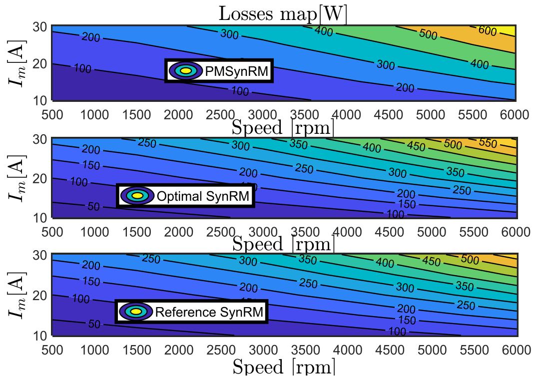

Figure 5. SynRM total losses maps for different rotor designs.

Moreover, the efficiency of SynRMs is better than induction motors [3] and is inferior compared to the permanent synchronous motors [9] as deduced in Figure 6. As the output power and total losses were affected with the rotor design, the efficiency of the machine depends on the rotor design as well (see Figure 6). At half rated condition the PMaSynRM's efficiency is around 95 %.

The power factor of the SynRMs depends on the saliency ratio (L_d/L_q) which is affected by the design of the rotor. The optimal SynRM has a higher power factor compared to the reference SynRM as it has the higher saliency ratio than the reference motor. However, it still has a low power factor about 0.68 at the rated conditions. Hence, adding PM in the optimized rotor reduces the phase angle between the voltage and current as shown in Figure 1. Consequently, the power factor is increased to about 0.91 at the rated conditions as observed in Figure 7 (PMaSynRM). This is a good indication for PMaSynRM to be attractive motor for industrial applications.

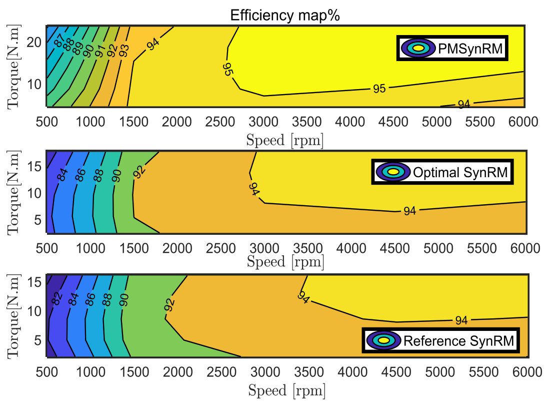

Figure 6. SynRM efficiency maps for different rotor designs.

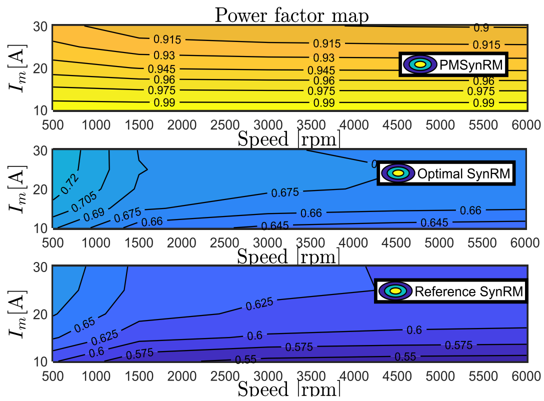

Figure 7. SynRM power factor maps for different rotor designs.

4. Experimental validation

The FEM results have been validated by experimental measurements using the test bench sketched in Figure 8. The measured and simulated validation results were obtained at fixed speed (2500 rpm), stator current (I_m = 20 A) and for different current angles. Figure 9 (a) shows the computed (FEM) and the measured phase voltage, output torque of the SynRM. It is observed that the phase voltage is inversely varied with the current angle. Figure 9 (b) shows the measured and computed values of the power factor of SynRM at different current angles. The power factor increases with the increase of current angle due to the increasing of the load torque. The measured and simulated values of the output torque of the SynRM are depicted in Figure 9 (c). The SynRM output torque increases with the increasing of current angle till it reaches a maximum value at optimal angle then it decreases again. The SynRM maximum torque does not happen at the current angle of 45°. The current angle should be controlled in order to attain a maximum torque per Ampère. Therefore, the efficiency and losses of the SynRM can be improved. The SynRM's efficiency is shown in Figure 9 (d). There is a good agreement between the simulated and the measured values. However, the difference between the measured and computed results is due to different reasons: the cutting and punching effects on the steel properties, the manufacturing tolerance and the measurement error. In addition, switching and mechanical losses are not included in simulation.

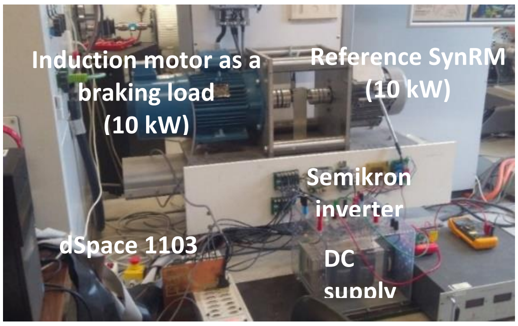

Figure 8. Photograph of the experimental setup.

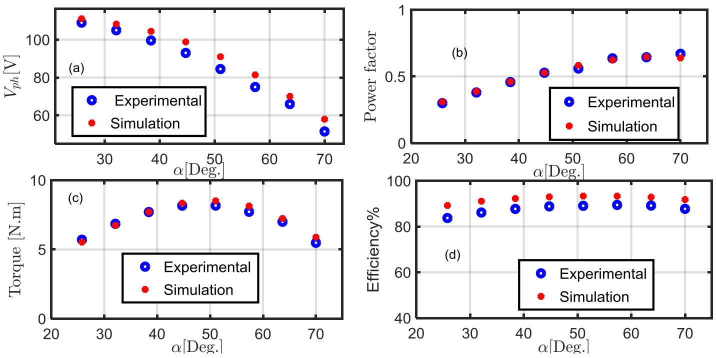

Figure 9. Computed and measured (a) phase voltage, (b) power factor, (c) output torque, and (d) efficiency of the SynRM at different current angles, current = 20 A and speed = 2500 rpm.

5. Conclusion

This paper has discussed the performance evaluation of Synchronous reluctance motors (SynRMs) with and without permanent magnets. Three different rotors having the same stator design and other parameters are considered. The three rotors are reference, optimized and optimized assisted by ferrite PMs (PMaSynRMs) in its flux-barrier. Different performance indicators for the machine are computed by FEM and compared at the same conditions. The performance indicators are efficiency, torque, total losses and power factor maps. It is found that the efficiency and power factor of the PMaSynRMs can reach higher than 95 % and 0.91 respectively at the rated conditions. This means that the PMaSynRMs can be considered as a good alternative for both the induction machines and switched reluctance machines. In addition, they can be good competitors compared to the permanent magnet synchronous machines due to lower cost. Finally, measurements are obtained and validated the FEM model.

References

[1] Ferrari M, Bianchi N, Doria A and Fornasiero E 2015 Design of synchronous reluctance motor for hybrid electric vehicles *IEEE Trans. Ind. Appl.* vol **51** no **4** pp 3030–40
[2] Ibrahim M N, Sergeant M N and Rashad E M 2015 Synchronous reluctance motors performance based on different electrical steel grades *IEEE Trans. Magn.* vol **51** no **11** Art. ID 7403304.
[3] Vartanian R and Toliyat H A 2009 Design and comparison of an optimized permanent magnet-assisted synchronous reluctance motor (PMa-SynRM) with an induction motor with identical NEMA frame stators *Proc. IEEE Electr. Ship Technol. Symp. (ESTS)* pp 107–12
[4] Jeong Y H, Kim K, Kim Y J, Park B S and Jung S Y 2012 Design characteristics of PMa-SynRM and performance comparison with IPMSM based on numerical analysis *Proc. 20th ICEM* pp 164–70
[5] Morimoto S, Sanada M and Takeda Y 2001 Performance of PM-assisted synchronous reluctance motor for high-efficiency and wide constant power operation *IEEE Trans. Ind. Appl.* vol **37** no **5** pp 1234–40
[6] Huang H, Hu Y Sh, Xiao Y and Lyu H 2015 Research of parameters and ant demagnetization of rare-earth-less permanent magnet-assisted synchronous reluctance motor *IEEE Trans. Magn.* vol **51** no **11** Art. ID 8112504
[7] Bertotti G 1988 General properties of power losses in soft ferromagnetic materials *IEEE Trans. Magn.* vol **24** no **1** pp 621–30
[8] http://www.bakkermagnetics.com/sites/default/files/downloads/ferrite_-_sintered_1.pdf (accessed on 1 June 2020)
[9] Ahonen T, Tamminen J and Montonen J 2014 Comparison of electric motor types for realizing an energy efficient pumping system *Proc. 16th Eur. Con. Power Electronic. Appl. (EPE'14-ECCE Europe)* pp 1–9
[10] Liu Ch T, Luo T Y, Hwang Ch C and Chang B Y 2015 Field path design assessments of a high-performance small-power synchronous-reluctance motor *IEEE Trans. Magn.* vol **51** no **11** Art. ID 8206504
[11] Lohninger R, Grabner H, Weidenholzer G, Silber S and Amrhein W 2015 Modeling, simulation, design of permanent-magnet-assisted synchronous reluctance machine *IEEE Trans. Ind. Appl.* vol **51** no **1** pp 196–203
[12] Dmitrievskii V, Prakht V and Kazakbaev V 2019 IE5 Energy-Efficiency Class Synchronous Reluctance Motor With Fractional Slot Winding, *IEEE Trans. Ind. Appl.* vol **55** no **5** pp 4676–84
[13] Prakht V, Dmitrievskii V and Kazakbaev V 2018 Mathematical modeling ultra-premium efficiency (IE5 class) PM assisted synchronous reluctance motor with ferrite magnets *2018 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED)* (Moscow) pp 1–6
[14] Ibrahim M N, Sergeant P and Rashad E M 2017 Design of low cost and efficient photovoltaic pumping system utilizing synchronous reluctance motor *2017 IEEE International Electric Machines and Drives Conference (IEMDC)* (Miami, FL) pp 1–7
[15] Ibrahim M N, Rezk H, Al-Dhaifallah M and Sergeant P 2019 Solar array fed synchronous reluctance motor driven water pump: An improved performance under partial shading conditions *IEEE Access* vol **7** pp 77100–15
[16] Ibrahim M N 2017 Design aspects of high performance synchronous reluctance machines with and without permanent magnets *Doctoral thesis*, Ghent university
[17] Ibrahim M N, Sergeant P and Rashad E M 2017 Relevance of including saturation and position dependence in the inductances for accurate dynamic modeling and control of SynRMs *IEEE Trans. Ind. Appl.* vol **53** no **1** pp 151–60